The contents of the Universe

- Chemical Elements: (other than H & He) 0.03%
- Neutrinos: 0.47%
- Stars: 0.5%
- Free H & He: 4%
- Dark Matter: 25%
- Dark Energy: 70%

We see that scattered through space, out to infinite distances, there exist similar systems of stars, and that all of creation, in the whole extent of its infinite grandeur, is everywhere organized into systems whose members are in relation with one another...

Immanuel Kant, 1755
Galaxies live in a variety of environments and their properties change with environment.

Galaxies change with wavelength:
- short, hot
- long, cold

Galaxies change with time:
- Present to 3 billion years ago
- 3 to 7 billion years ago
- 7 to 10 billion years ago
- 2-5 Gyr, 2-3 -120

Questions about Galaxy Formation and Evolution:
- How do galaxies form, and how do they change over time?
- Why do we see so many different kinds of galaxies? Are their differences a result of 'nature' or 'nurture'?
- How do the properties of galaxies depend on their environment?
- How do galaxies observed at different epochs relate to one another?

The Hubble Sequence:
Key point: most galaxies consist of two components, a disk and a bulge. Stars in the bulge are typically older ('redder light').
Simple picture of Hubble type

- Two parts to galaxies: bulge and disk
- Ellipticals all bulge, Sd galaxies basically all disk

Gravity + Cooling

- Small lumps (inhomogeneities): some regions of the Universe were slightly denser than others
- As the Universe expanded, these lumps grew larger and denser because of the force of gravity
- Difference between normal matter (baryons) and dark matter is that the baryons cool ("dissipation")

As gas cools, some regions get dense enough to form stars
Massive stars and quasars "reionize" the universe

Clumps gain angular momentum from interactions and "tidal torques"

Gas collapses to form a disk
What are Spiral Arms?

- All stars move at almost the same orbital speed, but stars near the center of the galaxy don’t have as far to go.
- If spiral arms rotated along with the galaxy, they would quickly “wind up” and become washed out.
- We don’t see any galaxies with such tightly wound arms.
- Instead of being a fixed pattern, spiral arms are like waves moving through the ocean.
- They are places where the gas has “piled up.”
- Therefore, we see a lot of new star formation and dust along the spiral arms.

Density waves are like a traffic jam.

- Dark matter halos and the galaxies they host are built up from mergers of smaller objects.
- Small things form first, big things form later (clusters are still forming).
- Merger rate declines with time.
Galaxy collisions

- Change in star formation rate: galaxy collisions can trigger powerful starbursts, leading to star formation rates 10-100 times higher than before the collision.
- Change in morphology: if the two galaxies have similar masses, the disks of both galaxies will be destroyed, leaving behind a spheroidal remnant.
Star formation in galaxies

- If the gas has enough angular momentum, the disk is stable, and star formation proceeds gradually over a long time period: spiral galaxy
- otherwise, the gas may collapse still further, forming stars rapidly and consuming all the remaining gas: elliptical galaxy or spheroid

Star Formation Rate of the Universe

[Graph showing the rate of star formation since the Big Bang]

Cluster Formation

[Image of a cluster of galaxies]

Galaxies form along filaments in the large-scale structure
A new Hubble Sequence?

Tidal features in galaxies

The Cartwheel Galaxy: a head on collision
Galactic cannibalism

- ‘central dominant’ (cD) galaxies in clusters ‘eat up’ hundreds of galaxies that fall into the center of the cluster
- Remnants of the massive galaxy’s lunch are still visible

The Future of the Milky Way?

- elliptical galaxies
  - big
  - old/red stars
- old dense regions (clusters)
- short star formation timescales

- irregular galaxies
  - small
  - young stars
- field
- long star formation timescales

Galactic Cannibalism:

- The Milky Way devouring Sagittarius
- The Large Magellanic Cloud
Summary

- galaxies form in places where the density becomes large due to gravitational collapse
- collapsing gas has angular momentum so naturally forms disks
- two ways to make spheroids:
  1. not enough angular momentum in gas
  2. galaxy collisions
- Merger rate of dark matter halos decreases with time
- Star formation also decreases in time (less merging, gas used up)